N72-28920

NASA TECHNICAL MEMORANDUM

NASA TM X-68116

NASA TM X-68116

AN OUT-OF-CORE VERSION OF A SIX-CELL HEAT-PIPE HEATED THERMIONIC CONVERTER ARRAY

by Erich W. Kroeger, James J. Ward, and Roland Breitwieser
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Seventh Intersociety Energy Conversion Engineering Conference
sponsored by the American Chemical Society
San Diego, California, September 25-29, 1972

AN OUT-OF-CORE VERSION OF A SIX-CELL HEAT-PIPE HEATED THERMIONIC CONVERTER ARRAY

Erich W. Kroeger
James J. Ward
Roland Breitwieser

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A thermionic system concept is described which incorporates a heat-pipe cooled fast spectrum reactor and six-cell thermionic converter modules located in the space radiator. Much of the technology being developed for the in-core thermionic reactor concept is directly applicable to this out-of-core concept, particularly the fuel and converter development activity. The major technology extension required is in the area of heat-pipes for cooling the reactor and carrying thermal energy from the reactor station to the converters. The performance characteristics of an out-of-core thermionic system at power levels between 40 and 70 kWe are summarized, the adaptation of in-core technology to the out-of-core concept is described and applicable heat-pipe technology programs now underway are discussed.

MOST OF THE NATIONAL EFFORT in thermionics over the past several years has been directed toward the development of a fast spectrum in-core thermionic reactor supplying 120 to 250 kWe for electrically propelled spacecraft. Significant accomplishments toward this goal are reported by Beard (1),* Holland (2), and Yang (3) in this session and related papers elsewhere in this Conference. But a recent study of the NASA mission requirements projected for the 1980's has indicated more potential uses for nuclear electrical power plants at power levels considerably lower than 100 kWe. Potential applications include communications, earth resource monitoring, orbit control and power for large space stations. Also recent re-examinations of the missions proposed for nuclear electric propulsion (NEP) including factors such as the space shuttle boost capability indicate that powers of 50 to 70 kWe are adequate for many NEP missions if the system specific weight can be kept low at these power levels.

Past studies directed toward modifying the in-core thermionic approach for low power operation indicated poor specific weights, reference (4), or required major extensions and changes in fuel element and converter technology, reference (5). A recent study (6) at the Lewis Research Center has indicated that if the thermionic converters are located out-of-core a high fuel volume reactor results, that is light, compact and should provide the low system specific weights required for NEP at the 50 to 70 kWe level, and adapts easily to power levels as low as 10 kWe for the nonpropulsive applications.

The observation that moving the thermionic converters out-of-core simplifies and compacts the reactor is not new. A number of papers published in the International Conferences on Thermionic Electrical Power Generation and the IEEE Thermionic Specialist Conferences have indicated this capability. But what is new in the concept proposed is that the fuel, its clad, the thermionic converter, and the converter parts retain a high degree of geometrical and material consistency for both in-core and out-of-core systems.

A key element in this extension of the in-core technology to a low power, light-weight, out-of-core system is the use of heat-pipes. The heat-pipes provide an easy technique of

*Numbers in parentheses designate References at the end of paper.

adapting existing hardware to new power plant configurations and also provide a unique means of achieving electrical isolation of the thermionic converters from the heat source, reference (7), previously a stumbling block in other out-of-core designs.

This paper briefly summarizes and updates some of the characteristics of the out-of-core adaptations of the in-core technology reported in reference (6), and presents some of the performance and design characteristics of a typical out-of-core, heat-pipe heated, heat-pipe cooled six cell thermionic converter array (TCA).

SYSTEM DESCRIPTION

A configuration suitable for NEP is shown in Fig. 1. Out-of-core thermionic power plants adapt to other configurations, but for the sake of consistency with several recent studies the side thrust spacecraft was chosen. The high-temperature radiator is 1 meter in diameter, and the length varies from 3.4 to 5.6 meters over the 40 to 70 kWe (unconditioned power) range. A compact heat-pipe cooled reactor is located at the rear of the high-temperature radiator, and since the reactor is designed on the basis of criticality, its size is constant over the reference power range. High-temperature heat-pipes connect the reactor to the bank of converters. An intermediate heat exchanger in the reactor area is used for power smoothing and to increase reliability. The reactor heat-exchanger and the converters are separated by 68.4 cm long heat-pipe sections for all powers. This provides adequate electrical isolation from the reactor for the low output voltage converter banks. The heat from the diode collectors is extracted by ferrous-alloy heat-pipes that also form the surfaces of the high-temperature radiator. Twenty electrically independent radiator sections are used to eliminate the usual insulating collector trilayers.

The electrical output from the converters is carried to the rear of the spacecraft by paralleled low-voltage leads.

Lithium hydride shielding is used to reduce payload and power conditioning neutron exposure while the mercury propellant decreases the effect of gamma radiation.

The thrustors are located centrally, followed by the power conditioning section containing heat-pipe cooled transistors located 5 meters from the center of the reactor. Two transistors are separately coupled to a toroidal transformer and thus form a compact low voltage switching segment. A shaped shield around the low voltage components provides additional radiation protection. The heat-pipes coupled to the transistors fan out to become a flat low-temperature radiator. The high voltage region of the power conditioning is located behind the low-temperature radiator. The scientific payload and antennae compose the final section of the spacecraft.

The vented, fast-neutron reactor shown schematically in Fig. 2 was selected for this study. The reactor core is an assembly of two elements, tungsten encapsulated fuel rods and tungsten heat-pipes.

Heat-pipes eliminate the usual electromagnetic (EM) pumps. This saves the electrical power required to operate inefficient EM pumps and eliminates shielded volumes required to house the pumps. Furthermore heat-pipes maintain a nearly constant temperature core, greatly simplify part-power operation, and if reactor shutdown is required, remove afterheat without the requirement for auxiliary electrical power to operate coolant pumps.

The reactor heat-pipes form two heat-exchangers at the ends of the reactor (Fig. 2a,2b and 2c). Since energy is extracted from both ends of the reactor, the heat-pipes and fuel rods can be made symmetric about the reactor center line. Short heat pipes with low axial heat flux result. Also, the reactor can be constructed in independent halves. The isolated halves in turn reduce the electrical leakage of the heat-pipe connected converter banks as discussed below.

The fuel element is 2.8 cm in width and 14.25 cm long (Fig. 2d). The tungsten fuel clad is modified from the cylindrical shape used in in-core thermionics to a cruciform shape and the fuel rods are assembled in a square array. The clad end section is similar but thicker than its equivalent in in-core thermionics. The metallic end sections are cross linked with tie rods to provide an articulated, yet firmly locked reactor structure. The last 5 cm of the fuel elements contain neutron reflecting material.

The reactor heat pipes are cylindrical in the fueled section and transform into a rectangular cross section to form the surfaces of the flat-plate cross-flow heat exchanger. The chemical vapor deposition process permits the fabrication of this somewhat unusual shape. The fuel elements and reactor heat pipes are nested together and are constrained radially by a

tungsten housing consisting of stacks of carefully machined washer-like pieces. The laminated tungsten discs are separated to provide stronger nucleonic coupling of the beryllia reflector with the core. The thickness of the laminated tungsten housing is selected to provide a hoop stress consistent with the hoop stress that has been found to give diametrical stability in various tungsten-clad uranium-carbide fuel-pin tests.

The assembled core is then enclosed with thin tantalum that forms a fission gas containment vessel. The beryllia reflector pieces are outside the tantalum enclosure. Eighty-two fuel elements and 89 reactor heat pipes are included in each reactor half (Fig.2c). The reactor core is nominally 28.5 cm in diameter and 29.0 cm long. A maximum uranium loading of 165 kg based on fully dense uranium carbide is available. But with metallic circumferential and end reflectors, only 115 kgs of uranium (235) are required to provide the necessary control margin and excess reactivity for fuel burnup. A fuel smear density of 69 percent (115/165) is therefore used in this design, with a substantial portion of the volume allocated to large central voids in the fuel element.

Typical NEP missions require the reactor to operate for the equivalent of 20,000 full-power hours. At 500 kWt this corresponds to a fuel burnup of 1.18×10^{20} fission/cc based on fully dense fuel in 69 percent of the available volume.

The reactor heat-pipe diameters are 1.2 cm and at low thermal powers operate very conservatively; an axial throughput of less than 4 kWt/sq cm for the highest power case treated. The surface flux in the cross flow heat exchanger adjacent to the reactor is about 106 w/sq cm at 500 kWt and is also within acceptable heat-pipe practice. Reactor heat-pipe surface temperatures of about 1850° K are used in the analysis.

The reactor heat-exchanger volume required for the transfer of the thermal power to the converter heat-pipes is small; so an additional set of heat-pipes is included in the cross-flow heat-exchanger. This extra set of heat-pipes does not leave the heat-exchanger area and is used for additional power smoothing and for parallel heat paths in the event of local heat-pipe failures. The overall dimensions of the resulting reactor and heat-exchanger are a diameter of 42 cm and a length of 54 cm.

Tantalum alloy heat pipes extend from each heat-exchanger to the cluster of converters. Lithium is the heat transfer fluid with argon added to ease heat-pipe startup and also to provide for a variable heated length. The first converter is separated from the reactor by a 68.4 cm long heat-pipe section which provides adequate electrical isolation between the converter and the heat source. The tantalum alloy heat-pipe consists of three sections: the evaporator, the adiabatic section, and the condensor section that is used to heat the emitters of the converters. The lengths and cross sections are shown in Fig. 3. Two temperatures and three axial throughputs were analyzed for pressure drop. Adequate pumping margins could be maintained for all cases. Typical lithium vapor conditions are 1840° K, 2400 torr. Heat loss from the adiabatic section is minimized by the use of multifoil insulation. Meteoroid damage protection is provided by the high-temperature radiator and the multifoil insulation that surround the heat-pipes.

Upon leaving the cross-flow heat-exchanger the pipes are separated, providing electrical isolation between the converters and the heat source. The electrical leakage losses are proportional to the square of the voltage, thus as indicated in reference (6) it is advantageous to also electrically isolate the reactor halves. An output voltage of 9.26 volts is then developed with a maximum "off ground" potential of only 2.07 volts. Even at this low voltage, leakage currents exist and require a slight increase in diode current resulting in reduced voltages. The local alterations to currents and voltages typically reduce the efficiency of the converter array to 0.935 of that of a no-leakage case.

The converter design consistent with in-core TFE emitter and collector diameters is shown in Fig. 4. It is a modification of a design described later in this paper. The primary changes are the use of lithium accumulators in the collector heat-pipe. These accumulators provide the excess fluid needed for effective heat-pipe operation and also act as lightweight current carrying leads. The 40 to 70 kWe power range permits larger radiator areas per unit power and, therefore, lower collector temperatures. The lower radiator temperatures permit the change from niobium alloy to stainless-steel. Recent performance data, reference (8), indicate that the deleterious effect of high collector temperatures on converter efficiency may often be underestimated for high-performance converters. This tendency is an additional reason for selecting low collector temperatures. The heat-

pipes that cool the converters are bonded to four smaller diameter heat-pipes that form the radiator surface. The four heat-pipes cover the supply pipe and provide redundant meteoroid shielding.

In the converter optimization analysis, several advantages of out-of-core heat-pipe heated diodes became apparent. First, a performance penalty is associated with low power thermionic reactors when converters are located in the core. This results because nuclear constraints require that the converters operate at power densities well below the peak efficiency condition. Heat-pipe heated converters permit operation at conditions that correspond to peak system efficiency. In effect the heat-pipe acts as a power transformer that adjusts the surface heat flux in the reactor to that needed for maximum performance of the thermionic-converter system. The heat-pipe also provides constant emitter temperature for each converter. Further, the converter can operate at the cesium pressure that corresponds to maximum performance since the thermal runaway problem of the coupled fuel-emitter cited in reference (9) is largely obviated by the out-of-core location. Also, the volumetric constraints associated with in-core thermionics are reduced. Thus large metallic cross sections in the electrodes can be used to minimize voltage drops. The additional use of relatively large volumes of liquid metals in the heat-pipes adjacent to the electrodes, as previously mentioned, results in low voltage drops at low specific weights. Nuclear fuel contamination of the electrode surfaces and emitter distortion caused by fuel swelling are also eliminated by the out-of-core design.

Another important advantage of the out-of-core converter location is the high efficiency that can be maintained at part power. If in-core systems are to achieve fractional power output, the core temperature must drop, and efficiencies fall. Liquid-metal-cooled systems degrade even more significantly since the pumps impose a very large parasitic load. The addition of an inert gas in the converter heat-pipes provides a simple solution to this problem. The inert gas collects at the end of an operating heat-pipe and establishes a well defined temperature front. If the gas loading and the heat pipe cross sections are properly chosen, significant motion of the thermal front can be achieved in the converter zone with small vapor-temperature changes. The converter heat-pipe shown in Fig. 3 requires an inert-gas accumulator located at the end of the pipe having a volume of only 1/3 liter. This volume provides complete activation of six converters at the design temperature of about 1800° K, then as the lithium vapor pressure is reduced by lowering the temperature 20° K the thermal front moves forward so that only a single converter (on each heat pipe) is left operating. Analytically the approximate loss in efficiency would be only 25 percent at 1/7 power. This requires a 20 percent decrease in output voltage to reduce the electrical leakage in the converter heat-pipe.

The design and operating characteristics of the shields, low-voltage leads, power conditioning radiator and thrustor subsystem are discussed in reference (6) so will not be repeated here.

Since the most challenging design problem is achieving low specific mass (kg/kWe) at low powers for NEP, estimates of the weights of the components and structure were made using methods consistent with other system studies such as presented in reference (10). Tabulated below are the specific masses, α , based on unconditioned power supplied to the thrustor for a thermionic converter emitter temperature of 1800° K.

Electrical Power, kWe	α, kg/kWe
40	33
50	29
60	25

These analytical projections are adequate for NEP. First order estimates for nonpropulsive applications at power levels as low as 10 kWe have also been made but, since they are so strongly dependent on specific applications, are not presented. However, by extrapolating from the NEP application performance levels, it can be seen that masses will be low.

TECHNOLOGY STATUS

As noted previously, the annular uranium carbide fuel pellet design selected for the heat-pipe cooled reactor is identical to that currently under development by NASA and the AEC for the in-core thermionic reactor concept. Only the fuel clad has been modified to a cruciform external shape in order to mate with reactor heat-pipes. Therefore, results from the extensive carbide fuel development program currently underway are directly applicable to the heat-pipe cooled reactor.

In regard to incorporating heat-pipes in the reactor and the heat-exchanger, one area of concern is thermal contact. An acceptable degree of thermal contact must be achieved between the tungsten fuel clads and the tungsten reactor heat-pipes in the core and the reactor and tantalum alloy converter heat-pipes in the heat-exchanger in order to avoid excessive temperature drops. In a preliminary bonding study conducted at 1800° K at a loading of 50 psi for 163 hours excellent bonds were achieved with platinum-coated tungsten-tungsten specimens, tungsten specimens separated by .0025 cm. thick tantalum foil and tungsten-tantalum alloy specimens. It is concluded that thermal contact can be achieved but additional effort is required to establish the minimum time, temperature and loading required to obtain bonding.

A number of CVD tungsten heat-pipes of reference geometry have been fabricated and tested. A picture of the components of one such pipe, utilizing a swaged wick in the evaporator and a grooved condenser, is shown in Fig. 5 The details of fabrication are presented in reference (11).

In order to increase the heat rejection capability of the condenser a set of tantalum fins were attached to the pipe as shown in Fig.6. With the fins in place the condenser rejects 2.8 kWt which corresponds to an axial heat flux based on vapor flow area in the evaporator of 9.5 kWt/cm^2, over twice that required for a 500 kWt reactor design. This pipe has accumulated over 4600 hours of operating time at 1825° K with no change in performance.

The converter heat pipes in the system design described are approximately 170 cm (~ $5\frac{1}{2}$ ft) long. At 150 and 350 kWe power levels (refs. (12) and (13)), the thermionic converters were located at a distance of 10 or more feet from the reactor. In support of these concepts, a 336 cm (~ 11 ft) long, lithium-filled T-111 heat-pipe was fabricated and placed on test. The pipe has an outside diameter of 0.75 inch, a wall thickness of .062 inch and was designed to carry 18 kWt at 1800° K. In this pipe an arterial liquid return system was used and helical wire coils were utilized as liquid distributors. A photograph showing the components of the pipe is presented in Fig. 7.

The 11 foot heat-pipe has undergone startup tests at temperatures up to 1700° K. These tests were conducted with thermal shielding around a $7\frac{1}{2}$ foot long adiabatic section and the condenser radiating heat to a water-cooled vacuum enclosure. The pipe is now being charged with argon at 0.1 atmosphere pressure and tests will be conducted to establish the influence of the inert gas addition on startup characteristics.

In support of the higher power out-of-core system concepts noted above a heat-pipe heated and heat-pipe cooled converter module shown in Fig. 8 was assembled in late 1970. The emitter was fabricated by chemically vapor depositing rhenium onto a tantalum sleeve which in turn, was shrink-fitted to a lithium-filled T-111 heat-pipe. The niobium collector was cooled by four completely independent, sodium-filled Nb-1Zr vapor chamber fins. The emitter outer diameter is 2.31 cm. and the active length is 10.2 cm. resulting in an emitter area of 73 cm^2. This converter module was performance tested at emitter temperatures between 1700 and 1850° K and is now being readied for life testing.

A second generation heat-pipe heated, heat-pipe cooled converter has been designed and subcomponent testing is underway. In this design, shown schematically in Fig. 4, several of the design features which proved satisfactory in the first generation converter as well as several features now being used in in-core converters have been used in combination. For example, the emitter in the second generation converter is 2.8 cm. in diameter and is a duplex tungsten structure consisting of a fluoride-derived CVD tungsten substrate onto which a chloride-derived CVD tungsten layer is placed. The emitter is somewhat longer than the in-core version, 7.88 cm. as compared to 5.08 cm., yielding an emitter area of 68.5 cm^2.

The collector is niobium; the collector structure being fabricated from coextruded niobium-stainless steel tubing. A single sodium-filled, tubular stainless steel vapor fin is used to cool the collector. This modification of the collector cooling system in terms of fin material, number and geometry results is a significant cost reduction over the cost of the first generation module.

A simple change in the emitter structure provides for the insertion of unenriched uranium carbide fuel into the structure and this converter design will be used to study the effect of fuel constituent diffusion through the emitter on converter performance in support of the in-core concept.

A sodium-filled stainless steel vapor fin, identical to that being considered for use in the second generation converter, has been fabricated,

filled with sodium and completed preliminary performance tests. The fin is now being readied for life testing.

SUMMARY

The performance characteristics of a heat-pipe cooled, out-of-core reactor thermionic system have been presented. The applicability of existing in-core technology to the out-of-core system concept, particularly in the areas of nuclear fuel and converter development, has been discussed. In addition, the status of required technology extensions related to heat pipes has been described. At power levels between 40 and 60 kWe projected nuclear electric propulsion spacecraft weights, utilizing this power system, range from 33 to 25 kg/kWe (based on net power delivered to the thrust subsystem). Therefore, the system could meet not only NEP missions but would be quite attractive for auxiliary power applications.

REFERENCES

1. D. S. Beard and J. J. Lynch, "Thermionic Reactor Program, An Overview." Paper to be presented at 1972 Intersociety Energy Conversion Engineering Conference, San Diego, CA, September 25-29, 1972.

2. J. W. Holland, "Thermionic Fuel Element Status Summary." Paper to be presented at 1972 Intersociety Energy Conversion Engineering Conference, San Diego, CA, September 25-29, 1972.

3. L. Yang and J. Chin, "Developmental Status of Thermionic Materials." Paper to be presented at 1972 Intersociety Energy Conversion Engineering Conference, San Diego, CA, Sept.25-29, 1972.

4. A. J. Gietzen, C. R. Fisher and W. G. Homeyer, "25 kWe Thermionic Power System for Space Base Application." IEEE Conference Record, 1970.

5. J. F. Mondt, M. L. Peelgren, "External Fuel Thermionic Reactor System." IEEE Thermionic Specialist Conference, San Diego, CA, 1971.

6. R. Breitwieser, "An Out-of-Core Thermionic Converter System for Nuclear Space Power." Third International Conference on Thermionic Electrical Power Generation, Jülich, Germany, June 1972.

7. R. Breitwieser, "Use of Heat Pipes for Electrical Isolation." IEEE Thermionic Specialist Conference, Miami, FL, 1970.

8. R. Breitwieser, "Correlation Expression for the Performance of an Etched-Rhenium Emitter, Niobium Collector Cesiated Thermionic Converter." NASA TM X-2380, 1971.

9. A. Schock, "Effect of Cesium Pressure on Thermionic Stability." IEEE Thermionic Specialist Conference, Framingham, MA, 1968.

10. "Thermionic Spacecraft Design Studies for Unmanned Nuclear Electric Propulsion." General Electric Co., GESP-625, June 1971.

11. R. J. Bacigalupi, "Fabrication and Testing of Tungsten Heat Pipes for Heat Pipe Cooled Reactor." IEEE Thermionic Specialist Conference, San Diego, CA, 1971.

12. J. J. Ward, R. Breitwieser and R. M. Williams, "Conceptual Design of a 150 kW(e) Out-of-Core Nuclear Thermionic System." IEEE Thermionic Specialist Conference, Miami, FL, 1970.

13. R. Breitwieser and E. Lantz, "A Design Study of a 350 kW(e) Out-of-Core Nuclear Thermionic Converter System." NASA TM X-52846, 1970.

E-7064

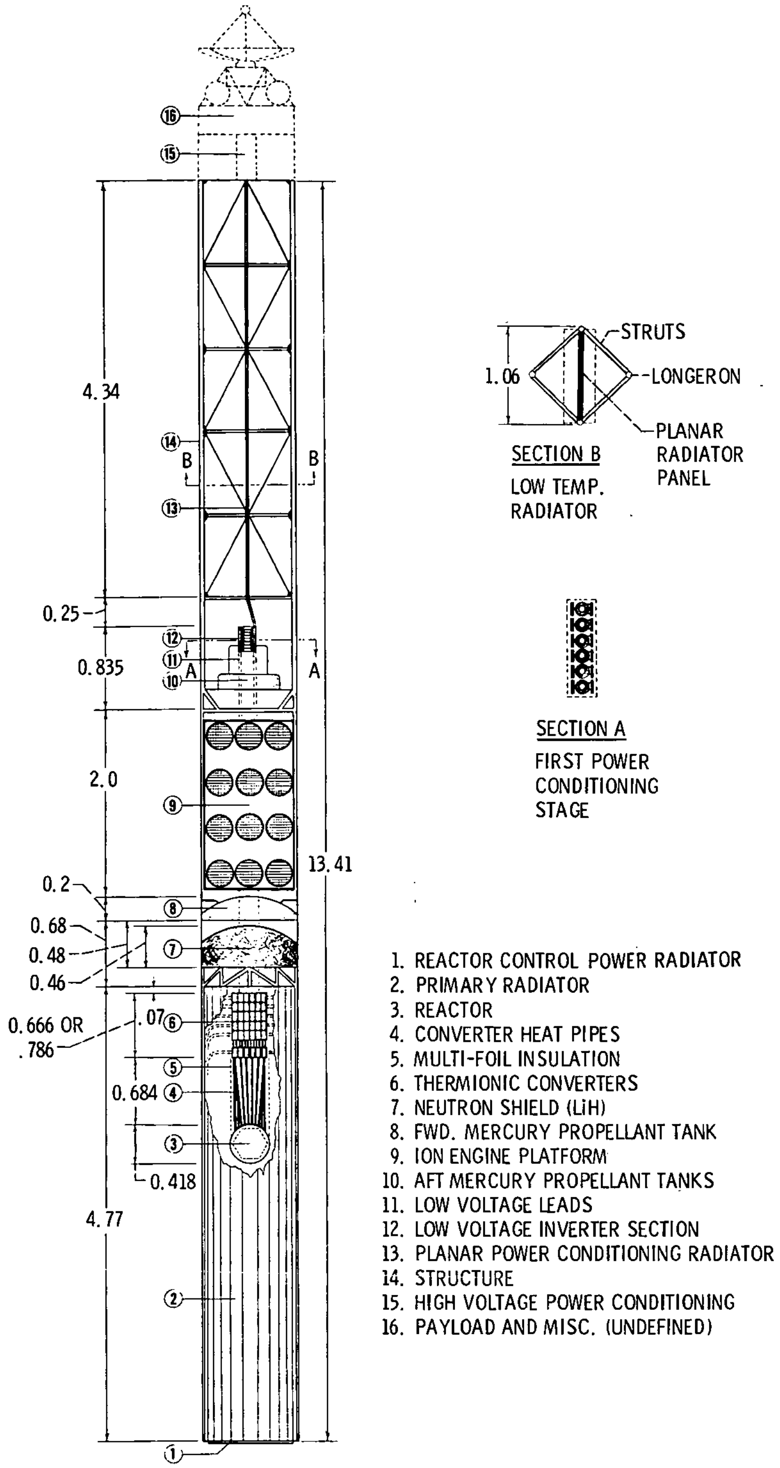
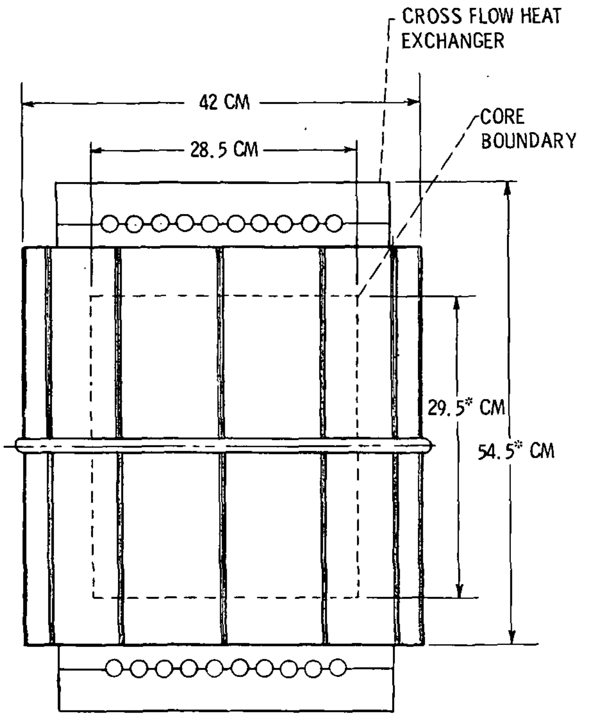
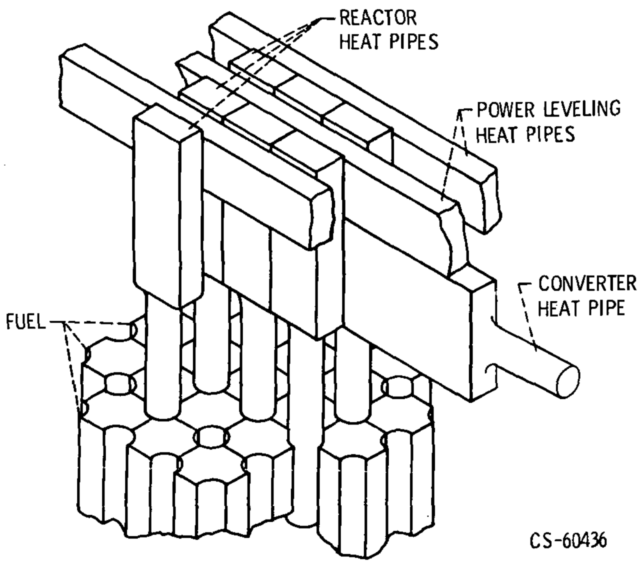


Figure 1. - NEP spacecraft configuration.



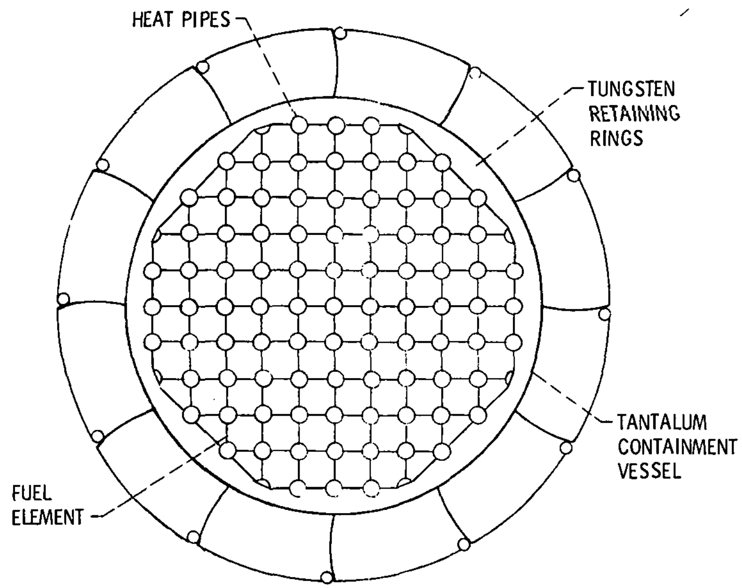
(a) EXTERNAL VIEW

*INCLUDES 0.5 CM SEPARATION.

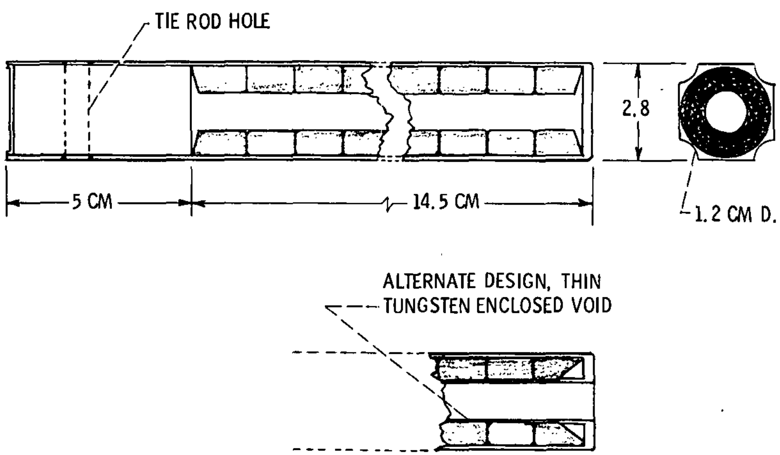


(b) SCHEMATIC DIAGRAM OF THE REACTOR CROSS-FLOW HEAT EXCHANGER; FOR CLARITY THE REACTOR HEAT PIPES ARE SHOWN PARTIALLY WITHDRAWN FROM THE CORE.

Figure 2. - Heat-pipe cooled, compact fast reactor.



(c) MIDPLANE VIEW OF THE REACTOR SHOWING FUEL, HEAT PIPES, TUNGSTEN RETAINING RINGS, AND BERYLLIA REFLECTOR.



(d) FUEL ELEMENT DESIGNS

Figure 2. - Concluded.

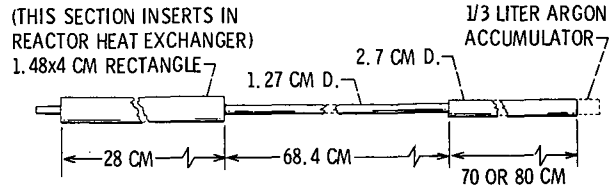


Figure 3. - Converter heat pipe dimensions.

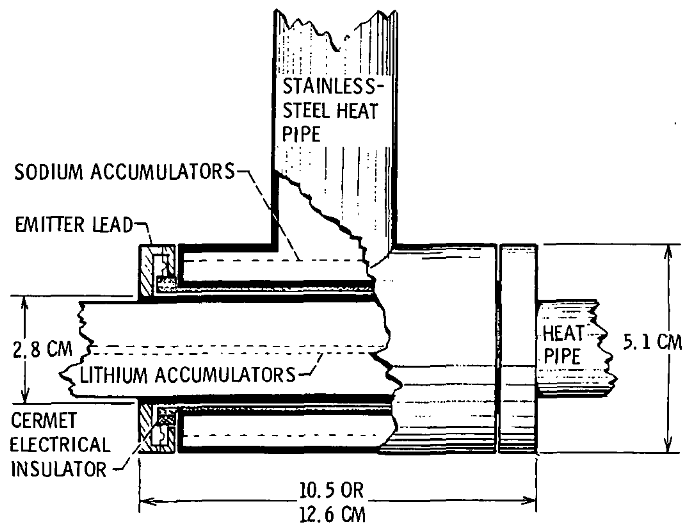


Figure 4. - Schematic diagram of the heat-pipe-heated and heat-pipe-cooled thermionic converter.

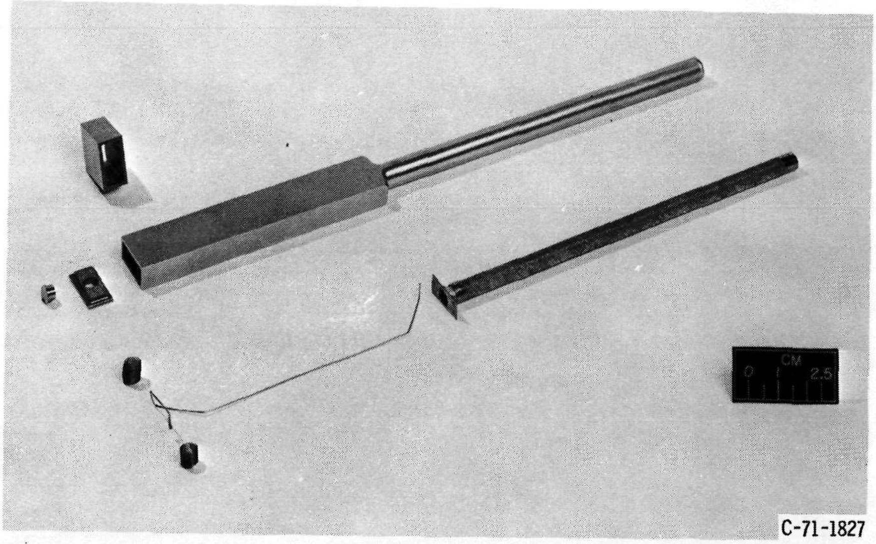


Figure 5. - Components of CVD tungsten reactor heat pipe.

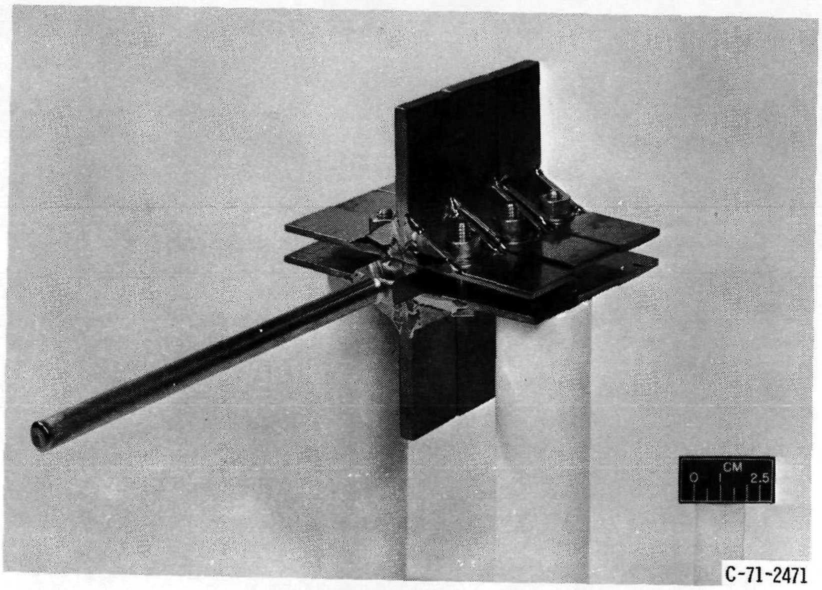
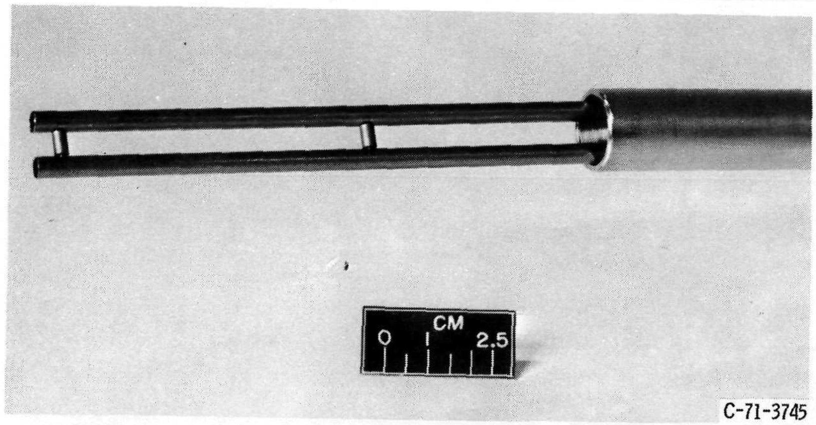


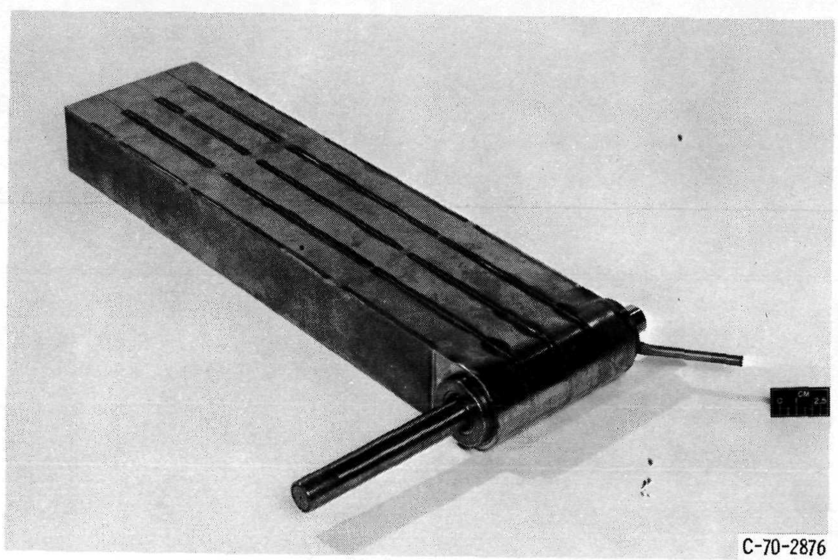
Figure 6. - CVD tungsten reactor heat pipe with fins attached to condenser.

E-7064



C-71-3745

Figure 7. - T-111 heat pipe with liquid return tubes paritally inserted.



C-70-2876

Figure 8. - Heat-pipe heated, heat-pipe cooled thermionic converter module.